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ORIGINAL PAPER

ANALYSIS OF THE LENGTH OF ORDER-PICKING PATHS DETERMINED USING THE S–SHAPE METHOD

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ABSTRACT. **Background:** Order-picking is a fundamental warehousing activity that accounts for in excess of 60% of total warehousing costs. Movements of pickers consume as much as half of the picking time. Thus determining picking paths is crucial. The most frequently used method is the S-shape one.

Material and methods: The average picking path length for 240 variants of the storage area (depot location, storage strategy), inventory (ABC-storage class sizes, probability of retrieving) and customer order (number of lines – 5, 10, 15) parameters was calculated. 100 simulations were carried out each time. MS Excel spreadsheet, along with macros (VBA) were used.

Results: The comparison were made of path lengths for a single block warehouse with 320 storage locations, Within-Aisle/Random storage strategies and low-level picking. Depot locations in the corner of a warehouse and in the middle of a front aisle were considered. The path lengths significantly varied with the variants that were analyzed. The shortest paths were observed for the Within-Aisle strategy, corner located depot, order sizes 5 or 10 and sizes of ABC-storage classes equal to 5/35/60% or 10/35/55% of all 320 storage locations under a retrieving probability of 90/5/5%.

Conclusions: Better and worse picking variants exist, influencing significantly the length of picking paths determined using the S-shape method. In general, the depot location is less important, even though the best variant assumed a corner location, while a location in the middle of a front aisle gives shorter paths on average. A much more important factor is the storage strategy. Lack of the strategy (randomness) substantially extends path lengths (by 50% on average).

Key words: warehousing, order picking, S-shape method, picking paths length.

INTRODUCTION

Order-picking is one of the fundamental activities carried out in warehouses. It is a sub-process of the superior warehouse process consisting in retrieving (block-stacked or racked) items from the inventory to fulfill a customer order (qualitatively and quantitatively) [Coyle et al. 2002].

The general picking strategies are [Emmett 2005, Parikh, Meller 2008, Zając 2014]:

- single-order/piece/discrete picking, the most common picking strategy, where one warehouse picker retrieves items (line by line in an order) to fulfill a single order at once,
- multi-order/batch picking, the strategy where one warehouse picker retrieves items simultaneously and sorts them afterwards to fulfill multiple orders,
- cluster picking, the strategy where one warehouse picker retrieves items simultaneously and sorts them at the same time to fulfill multiple orders; this strategy is similar to the previous one, the only difference lying in the moment of sorting the items collected,
- parallel zone/wave/consolidation picking, the strategy where many warehouse pickers retrieve items in particular storage zones

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simultaneously and merge them afterwards to fulfill a single order,
- sequential zone picking, the strategy where many warehouse pickers retrieve items in particular storage zones consecutively and merge them simultaneously to fulfill a single order; the strategy is similar to the previous one, the only difference lying in the moment of merging collected items,

and many other strategies, which can also be generally divided into a one- and two-stage picking strategies differing in terms of the number (single or many) of orders picked at once and the number of times the retrieved items are handled, thus if sorting of them is required or not [Gudehus, Kotzab, 2009].

Particular order picking strategies can be implemented [Emmett 2005, Garbacz, Łopuszyński 2015, Kostrzewski, Kostrzewski 2014]:
- in a warehouse storage or picking areas or both,
- as picking by order or by item,
- as person-to-goods or goods-to-person picking.

The most common picking strategy is single-order/piece/discrete picking by order carried out as a low/ground-level, person-to-goods in a warehouse storage area [De Koster et al. 2007]. A picker using a picking list and a load carrier (e.g. pallet, plastic or paper box, …) goes to consecutive storage locations (according to the picking list), where inventories are kept. The picker retrieves the appropriate quantity that has been ordered (number of items) of goods and places them on or in a carrier, and in this way, visits all the storage locations on the picking list.

Order-picking, including setup, travel, search, pick and other activities is the most time- and thus labor- and cost-consuming warehouse sub-process. It is commonly recognized that it usually takes 50-60% of the total warehouse operating time, labor or costs on average [Oudijk et al. 2019, Tompkins et al. 2010], whereas travel (walking) activity separately consumes as much as a half of the picking time [De Koster et al. 2007, Dukic and Cedomir 2007, Le-Duc 2005, Tompkins et al. 2010].

METHODS FOR DETERMINING ORDER-PICKING PATHS

There are many methods for determining order-picking paths. The fundamental ones are the following [De Koster et al. 2007, Hall 1993, Le-Duc 2005]: S-shape, Midpoint, Return, Largest Gap, Combined and Optimal. Among these, one of the simplest and frequently used is the S-shape (or the Traversal) method. In this method, a warehouse picker travels (walks or rides) from a starting point (a depot/base/I/O – Input/Output/P/D – Pick-up/Drop-off point) through particular aisles in which items to be retrieved are located, traversing them only once (in one direction, with no returns – optionally with an exception for the last one aisle to be traversed) and finally coming back to the starting point. This route produces the characteristic shape of an order-picking path resembling the "S" letter. The S-shape method, like any other, has its advantages and disadvantages, which are presented in Table 1.

Table 1. Advantages and disadvantages of the S-shape picking method

Advantages	Disadvantages
Simple order picking path determining	Fixed (inelastic) when determining order picking paths
Easy to implement in practice – intuitive to pickers	Aisles containing at least one pick have to be traversed entirely – optionally with an exception for the last one aisle to be traversed
Implementable for a one- (including narrow) and a two-way aisles	Odd number of aisles to be traversed requires empty movements (adding a one aisle to be traversed with no picks or optionally with an exception for the last one aisle to be traversed in a U-turn manner)
For high numbers of order lines gives as good results as the Optimal method	Sensitive to congestion (causing blocking of pickers)
Aisles with no items to retrieve can be skipped	In case of one-way (narrow) aisles even numbers of them are required to be skipped due to no picks

Source: author's research

LITERATURE SURVEY

A low-level, picker-to-parts (also called person to goods) order-picking system employing humans and with multiple picks per route is commonly recognized to be the most frequently used in warehouses worldwide. According to De Koster et al. [2007] and also to Grosse et al. [2015], over 80% of all order-picking systems in Western Europe are like this. In this system, the travel distance is the distance a warehouse picker travels (walks or rides) from a starting point (a depot) through particular aisles in which the items to be retrieved according to customers' orders are located, before coming back to the starting point. The issue of picking distance has been extensively studied for the last decades starting from the 1970s, when one of the first methods for calculating its length was proposed by Gudehus [1973].

The travel distance (and its minimization) has become the most common objective for warehouse and picking process planning/optimization. The distance is sometimes recalculated into the travel time [Hall 1993]. The distance, or more directly, the picking time, along with the accuracy of picked orders, is crucial for the service level/quality of the whole process (the faster an order is completed, the sooner it is available for shipping). As Gajšek et al. [2017] recognized, although various activities other than travel may substantially contribute to order-picking time, travel is often the dominant component. Moreover, travel time costs labor hours but does not add value. For manual order picking systems, the travel time is an increasing function of the travel distance. Consequently, the travel distance is often considered as a primary objective in warehouse design and optimization.

The travel distance can be divided into two or three components. According to Roodbergen and Vis [2006], they are the distance traveled within the aisles and the distance traveled in the cross-aisles. According to Sadowsky and Hompel [2011], however, there are three components: the basic distance, the within-aisle distance and the across-aisle distance. The basic distance, which makes the only difference, depends on the storage area layout, and is the distance from the depot to the first (horizontal) aisle to be visited (traversed).

There are a few factors, such as warehouse operating policies, crucial for the travel distance to be covered during the picking process. Among them the most frequently pointed out and analyzed in the literature are the following: the warehouse layout and the three strategies of storage, routing/sorting and batching [Burinskienė et al. 2018, Henn 2012, Le-Duc and De Koster 2005, Petersen 1997, Petersen and Aase 2017, Petersen and Schmenner 1999, Rao and Adil 2013b]. However, there is also another factor that is not a part of operating policies, but is an independent one element, namely, the demand (customer orders) and its parameters (e.g. order sizes and the frequency of occurrence of particular SKUs in orders). This factor is studied in this research.

This factor, i.e. demand, is far more rarely addressed in the literature than the other four mentioned above. One of the examples of the research dealing with it is the study by Dijkstra and Roodbergen [2010], where the storage location assignment problem is analyzed in order to minimize the average route length traveled by the order pickers while retrieving items from locations in a warehouse. The authors developed a complex distance function that depends on the layout of a warehouse, the routing method employed, the demand frequencies of all items, and the item-to-location assignment itself. The influence of the demand patterns and order pick sizes on the picking travel distance is also studied by Le-Duc and de Koster [2005] as well as by Petersen and Schmenner [1999].

As far as the warehouse layout design is concerned, the number and relative orientation of picking aisles, the locations of the cross aisles and the position of pick-up/drop off (P/D) points (usually in the corner of a warehouse) are taken into account [De Koster et al. 2007, Rao and Adil 2013a]. When considering the routing strategy, the methods for determining the order picking paths (S-shape, Midpoint, Return, Largest Gap, Combined and Optimal one) mentioned in the previous section are usually considered [De Koster et al. 2007, Le-Duc 2005]. However, in practice, only simple routing heuristics are used, such as the S-shape and the Return [Moeller 2011]. Moreover, Burinskienė et al. [2018] indicate that the methods that are used usually involve the logic of the Largest Gap, Midpoint or S-shape one. These issues/factors influencing the length of picking paths are also addressed in this research.

Thus, the aim of this paper is to search for the quantitative influence of such specific factors as the storage strategy, the depot location, the order size, the size of ABC-storage classes, the probability of retrieving items belonging to particular ABC-storage classes and combinations of them on the length of picking paths determined using the S-shape method. The three last factors come from the demand pattern and are independent (hard to control) ones that are much more rarely addressed in the literature.

ANALYSIS

The analysis was carried out for a single block warehouse layout (with dimensions of 44.8 x 24 m, c. 1,075 m2) with 320 EUR-palette storage locations (with dimensions of 1.3 x 0.9 m) and 10 two-way 3m wide aisles, including vertical and horizontal, the front and the back, ones. Thus the vertical aisles are 18 m long.

The Within-Aisle and the Random storage strategies with the ABC-based storage classes (assortment groups) were considered. The low-level and person to goods single order picking system was used. The Within-Aisle storage strategy assumes that the ABC-storage classes are located aisle by aisle, starting from an A-class next to depot and locating B- and C-classes further from it. In the case of the depot located in the middle of the a front aisle, the above holds for both the left and the right sides (directions) from it. The Random storage strategy assumes that the items from a particular ABC storage classes are located evenly throughout the whole storage area (with a uniform distribution, so the average distance to particular ABC-storage classes is almost the same).

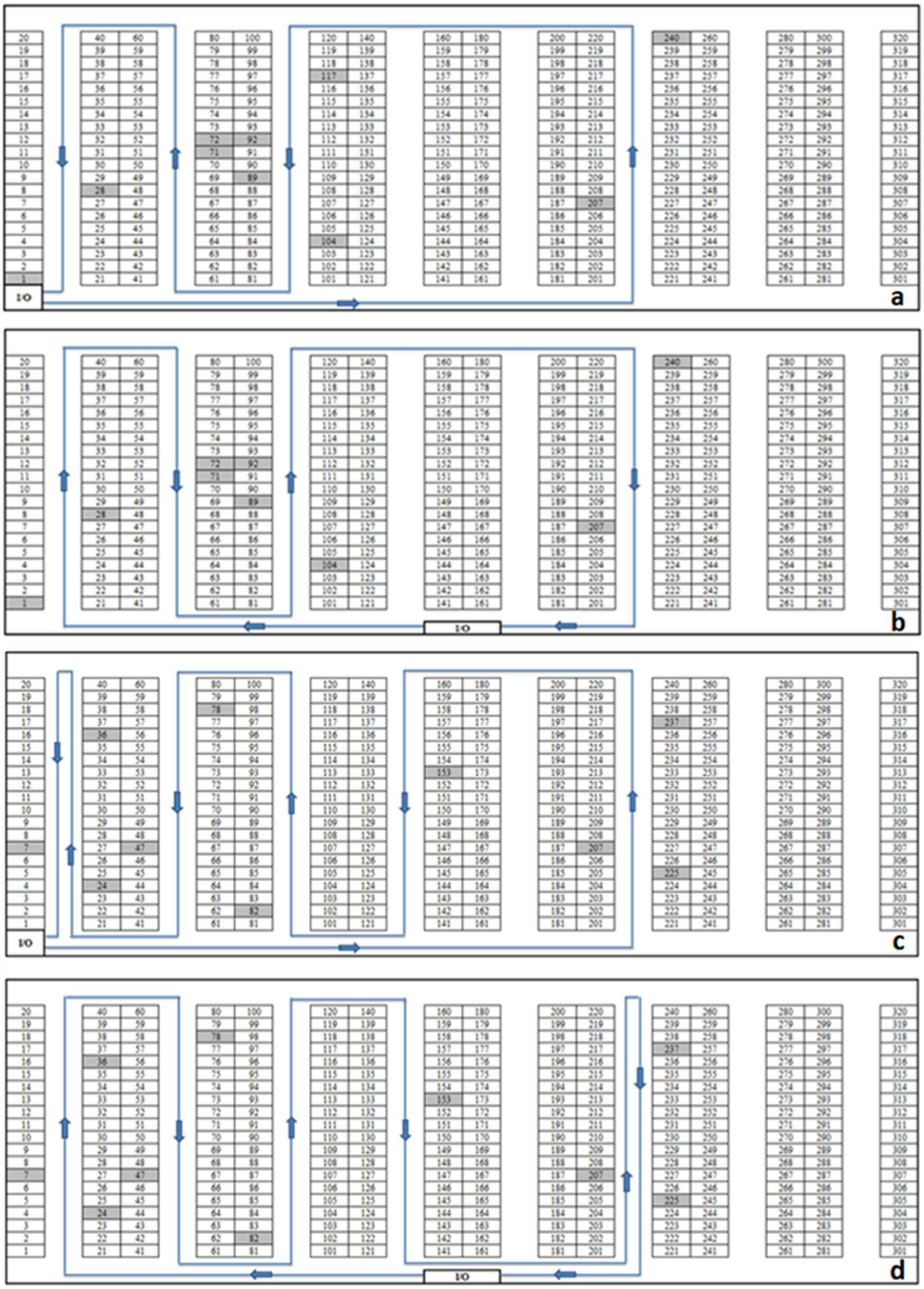
The depot located in the corner of a warehouse (the bottom left one) and in the middle of a front aisle was taken into consideration (see Fig. 1 where the S-shaped picking order paths for odd and even numbers of aisles to be traversed to pick an exemplary, randomly selected items/storage locations are presented as well). Such a layout is commonly used in the literature [Henn 2012, Zare Mehrjerdi et al. 2018], although usually with the depot located in the corner of a warehouse. Locating the depot in the middle of a front aisle is rather rare (see, for example Roodbergen and Vis 2006).

Orders to be picked with a different numbers of lines/SKUs (including 5, 10 and 15 lines) have been considered. The storage locations of the particular items on an order are drawn at random, taking into account such factors as the sizes of ABC storage classes and the predefined probability of retrieving items belonging to each class. It is assumed that when the whole orders are picked at once by a one warehouse picker traversing all storage locations characteristic for items on the order, this gives single-order/piece/discrete picking. Picking paths are determined using the S-shape method.

The 240 variants were analyzed, which are combinations of the following parameters, i.e. the different:

- storage strategies (2),
- depot (I/O) locations (2),
- order sizes, i.e. number of lines/items/SKUs (3),
- sizes of ABC-storage classes, i.e. percentage of all SKUs/storage locations (5),
- probability of retrieving items belonging to a particular ABC-storage classes (4),

On each occasion, items (in fact, their storage locations) on the order were drawn at random under the aforementioned parameters assumed for the current variant values. For the Random storage strategy-based variants for every 20 different orders drawn, the locations of SKUs were also changed (20 different orders multiplied by 5 different locations of SKUs giving 100 repetitions of the analysis).



Source: author's research

Fig. 1. Exemplary order picking paths a-b) for even and c-d) for odd number of (vertical) aisles to be traversed

The way the variants are constructed is presented in Table 2. The variants are the same for both depot (I/O) locations - in the bottom-left corner of a warehouse and in the middle of its front aisle and both storage strategies (i.e. the Within-Aisle and the Random ones) as well.

Table 2. Variants of analysis

Size of ABC-storage class	Probability of retrieving	Order size
A/B/C 5/35/60%	A/B/C 60/20/20%	5
		10
		15
	A/B/C 70/20/10%	5
		10
		15
	A/B/C 80/15/5%	5
		10
		15
	A/B/C 90/5/5%	5
		10
		15
A/B/C 10/35/55%	Combinations of the values of particular parameters as above	
A/B/C 20/30/50%		
A/B/C 30/25/45%		
A/B/C 40/20/40%		

Source: author's research

Based on the above assumptions, the length of picking paths for each variant was calculated for every repetition of the analysis. Finally, the average values were calculated.

The length L of picking paths was calculated based on equations 1 and 2, depending on the location of the depot. Equation 1 concerns a depot located in the corner of a warehouse (the bottom-left one), while Equation 2 concerns a depot located in the middle of a front aisle. It is assumed that order pickers retrieve items from both sides of the aisles without moving sideways (move in straight lines in the exact middle of the aisles).

$$L = 2 \cdot (x-1) \cdot (2 \cdot SL_L + Av_W) + z \cdot (Av_L + Ah_W) \quad (1)$$

$$L = 2 \cdot (x-y) \cdot (2 \cdot SL_L + Av_W) + z \cdot (Av_L + Ah_W) \quad (2)$$

where:

- L — length of picking path determined using the S-shape method [meters],
- x — the highest (rightmost) number of a (vertical) aisle to be traversed (aisle containing at least one item to be picked); x = 2, 3, … [–],
- y — the lower (leftmost) number of a (vertical) aisle to be traversed (aisle containing at least one item to be picked); y < x, y = 1, 2, 3, …, x – 1 [–],
- z — number of (vertical) aisles to be traversed; $z \in \{2n : n \in N\}$ [–],
- SL_L — storage location length [meters],
- Av_W — aisle (vertical) width [meters],
- Av_L — aisle (vertical) length [meters],
- Ah_W — aisle (horizontal – front/back) width [meters].

The formulas (1) and (2) are based on the way of calculating the S-shape picking distance presented by Zhang et al. [2017], and also used by Zare Mehrjerdi et al. [2018]. However, the proposed formulas are first extended to take into account aisles' width (which is not included in the original formulations) and, secondly, corrected: the original formulas are somehow imprecise. as they assume the number of aisles in which there are pick locations that must be visited for picking (containing at least one item to be picked) is equivalent to the number of aisles (vertical ones) to be passed by/crossed. It holds true then and only then that those aisles are consecutive ones (with no aisles to be skipped due to having no items to pick). Finally, the formulas are simplified, skipping the U-turn at the last visited aisle (it is assumed that the number of traversed aisles is even – if not, one extra aisle with no picks is added). It does not matter here, since the S-shape method is not compared with the other methods of determining order-picking paths. However, it is recognized in the literature that an S-shaped route shortens the travel distance if the U-turn at the last visited aisle prevents pickers from travelling along it twice [De Koster et al. 2007]. On the other hand, the formulas (1) and (2) can be used for both one- (also narrow) and two-way aisles.

RESULTS

Tables 3 and 4 present the study results, i.e. the average length (in meters) of order-picking paths for the Within-Aisle and the Random storage strategies combined with a depot located in the corner of a warehouse (the bottom-left one) and in the middle of a front aisle, accordingly.

Table 3. The average length (in meters) of order picking paths for a depot located in the corner of a warehouse (the bottom left one)

The depot (I/O) location – the bottom left one corner of a warehouse											
Probability of retrieving A/B/C%	Order size	Size of ABC-storage classes A/B/C%									
		5/35/60		10/35/55		20/30/50		30/25/45		40/20/40	
		WA*	R*	WA	R	WA	R	WA	R	WA	R
60/20/20	5	109	126	112	126	114	124	119	129	125	125
	10	123	156	130	155	138	155	144	155	151	155
	15	141	169	143	171	152	168	156	168	164	170
70/20/10	5	47	128	52	128	75	124	85	127	92	129
	10	111	158	114	155	124	155	131	154	140	157
	15	112	170	113	170	128	169	136	167	140	169
80/15/5	5	45	127	49	125	73	126	85	126	92	128
	10	58	159	69	158	82	153	92	153	106	156
	15	108	172	113	169	124	168	134	169	141	168
90/5/5	5	32	130	32	130	42	128	64	126	75	127
	10	32	161	32	155	42	154	71	154	82	154
	15	106	172	111	171	116	168	133	169	142	170

* Within-Aisle storage strategy ** Random storage strategy
Source: authors' research

Table 4. The average length (in meters) of order picking paths for a depot located in the middle of the front aisle

The depot (I/O) location – the middle of a front aisle											
Probability of retrieving A/B/C%	Order size	Size of ABC-storage classes A/B/C%									
		5/35/60		10/35/55		20/30/50		30/25/45		40/20/40	
		WA*	R*	WA	R	WA	R	WA	R	WA	R
60/20/20	5	85	116	93	113	95	113	101	118	111	114
	10	105	151	121	150	128	150	135	150	140	149
	15	127	167	136	167	142	165	149	165	159	167
70/20/10	5	43	120	59	113	66	114	75	117	84	119
	10	91	154	98	149	105	151	119	149	128	151
	15	95	168	101	166	112	166	125	163	135	166
80/15/5	5	41	119	53	114	63	116	75	117	84	116
	10	55	156	71	152	77	147	88	148	107	150
	15	91	170	97	165	107	165	122	165	131	165
90/5/5	5	33	123	40	116	41	120	61	116	75	116
	10	33	157	41	150	41	151	69	150	82	149
	15	83	170	92	167	96	165	116	165	127	167

* Within-Aisle storage strategy ** Random storage strategy
Source: authors' research

It can be observed in Tables 3 and 4 that the average length of order-picking paths significantly varies. Much better results for shorter (by 34%) average order-picking paths were obtained for the Within-Aisle storage strategy (97 meters long on the grand average) than for the Random storage strategy (148 meters long on the grand average). That corresponds to the study by Rao and Adil [2013b], who established that a maximum of two to three classes (ABC) is sufficient to gain a significant (10-40%) improvement over the Random policy in pick travel distances for practical pick sizes. Also the better the results, the shorter the average order picking paths were obtained for the depot located in the middle of a front aisle (119 meters long on the grand average) than for the depot located in the bottom left corner of a warehouse (126 meters long on the grand average). This in turn corresponds to the research by Petersen and Schmenner [1999], who recognized the middle location to be better by 4.4%, as far as the picking distance is concerned over the corner one (here this difference is 5.9%). However, their research concerned the six methods mentioned earlier in this paper for determining the order-picking paths together, so the result is the grand average.

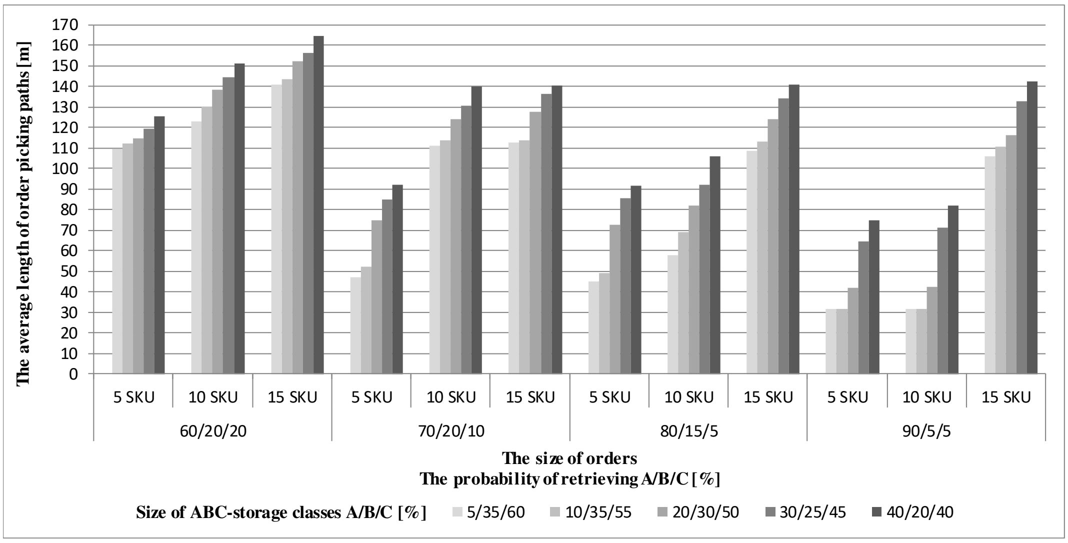
But the best results, the shortest average order-picking paths were obtained for the four variants of the order-picking system defined by the following combinations of the parameters analyzed:

- the Within-Aisle storage strategy,
- the depot located in the bottom left corner of a warehouse,
- the order sizes equal to 5 or 10,
- the sizes of ABC-storage classes equal to 5/35/60% or to 10/35/55% of all storage locations,
- the probability of retrieving items belonging to a particular ABC-storage classes equal to 90/5/5%.

These four variants of the order picking system result in the average length of the order-picking paths equal to 32 meters. Very similar or even the same results (within the error limits) were obtained for the 2 variants characterized by 5 or 10 order sizes, variants of the Within-Aisle storage strategy, sizes of ABC-storage classes equal to 5/35/60% of all storage locations, the probability of retrieving items belonging to a particular ABC-storage class equal to 90/5/5%, but with the depot located in the middle of a front aisle (33 meters).

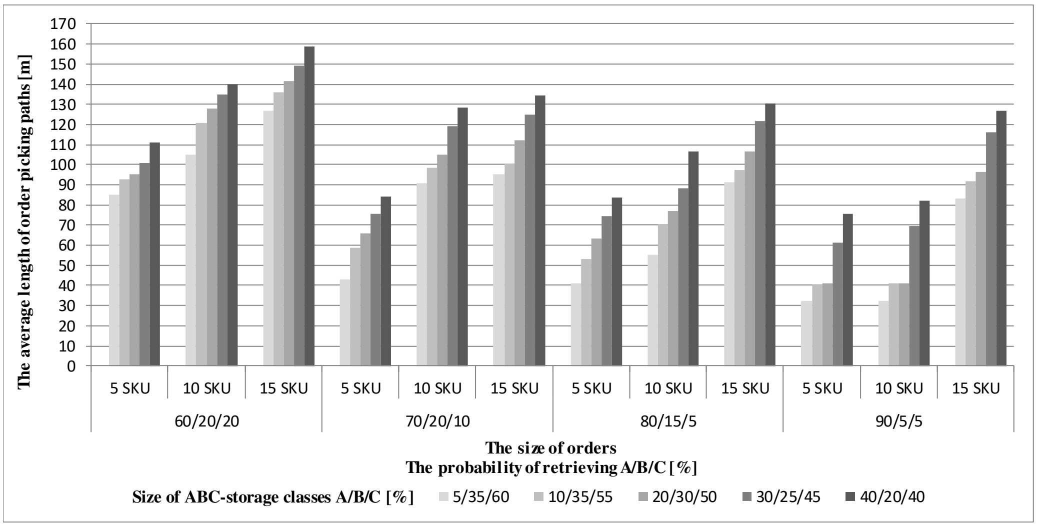
As far as the Random storage strategy is concerned, in the results obtained, the average order-picking path length was 148 meters on average. In this case, slightly better results, shorter average order-picking paths were obtained for the depot located in the middle of a front aisle (145 meters long), whereas for the depot located in the bottom-left corner of a warehouse, the average order-picking paths were 4% longer (151 meters long).

Fig. 2 and 3 present the same results in a graphical way, i.e. the average length (in meters) of order-picking paths for the Within-Aisle storage strategy combined with a depot located in the corner of a warehouse (the bottom-left one) and in the middle of a front aisle, accordingly.



Source: authors' research

Fig. 2. The average length (in meters) of order picking paths for the Within-Aisle storage strategy and the depot located in the corner of a warehouse (the bottom left one)



Source: authors' research

Fig. 3. The average length (in meters) of order picking paths for the Within-Aisle storage strategy and the depot in the middle of a front aisle

As far as the characteristics of the orders (their sizes) and inventories (sizes and probability of retrieving ABC-storage classes) are concerned, the shortest average length of order-picking paths can be found for a narrow A-storage class (covering a small number of SKUs), the high probability of retrieving items belonging to this class and short orders (with a small number of lines). The wider the A-storage class, the lower the probability of retrieving items belonging to this class and the longer the orders, the longer the picking paths. However, for the Random storage strategy, the differences in picking paths' lengths are smaller and they depend mostly on the order size than on inventory characteristics.

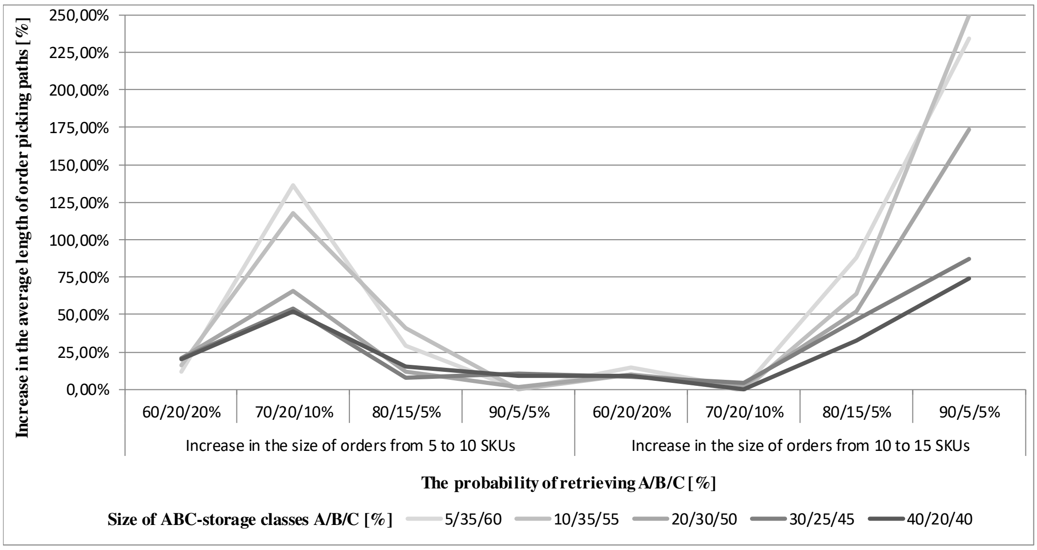
For the Within-Aisle storage strategy, the highest increase in the picking paths' length when changing the order size from 5 to 10 lines was observed for the probability of retrieving items belonging to a particular ABC-storage classes equal to 70/20/10%. However, when changing the order size from 10 to 15 lines, what was the critical for picking paths' length was the probability of retrieving equal to 90/5/5%. On the other hand, the smallest increase in the picking paths' length when changing the order size from 5 to 10 and from 10 to 15 lines was observed for the opposite probabilities of retrieving - 90/5/5% and 70/20/10%, respectively. The changes described in the picking paths' length were observed for both locations of the depot (in the corner of a warehouse and in the middle of its front aisle). In particular, the highest increase (136%) in the picking paths' length when changing the order size from 5 to 10 lines was observed for the sizes of ABC-storage classes of 5/35/60% and the depot located in the corner of a warehouse (under the probability of retrieving given above). When changing the order size from 10 to 15 lines, the length critical for picking paths increased by 250% , where the sizes of ABC-storage classes equal to 10/35/55% (at the same location of the depot and the probability of retrieving given above). For the Random storage strategy, the increase in the picking paths' length was quite different (in general, significantly smaller) in comparison to the one for the Within-Aisle storage strategy. When changing the order size from 5 to 10 lines, the picking paths' length increased by:

- 20-26% for the depot located in the corner of a warehouse,
- 26-34% for the depot located in the middle of its front aisle,
- whereas when changing it from 10 to 15 lines, the paths' length increased by:
- 7-10% for the depot located in the corner of a warehouse,
- 8-12% for the depot located in the middle of its front aisle.

Comparing the Within-Aisle and the Random storage strategies, the narrower the A-storage class and the higher probability of retrieving items belonging to it, the more significant difference in the average length of picking paths. The most significant differences were equal to:

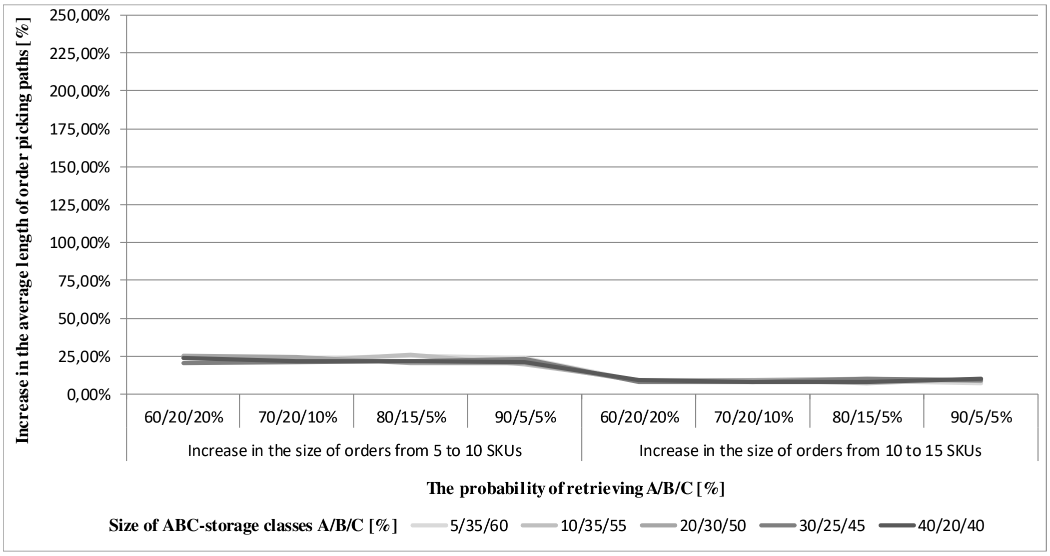
- 129 meters for the depot located in the corner of a warehouse, the size of ABC-storage classes equal to 5/35/60% and the probability of retrieving equal to 90/5/5%,
- 125 meters for the depot located in the middle of a front aisle and the same size of ABC-storage classes and the probability of retrieving.

Figs. 4-7 present the changes in the average length of order-picking paths, depending on the order size. The value (Y) axis scale in Figs. 4-7 have been set to the same range to make the charts comparable.



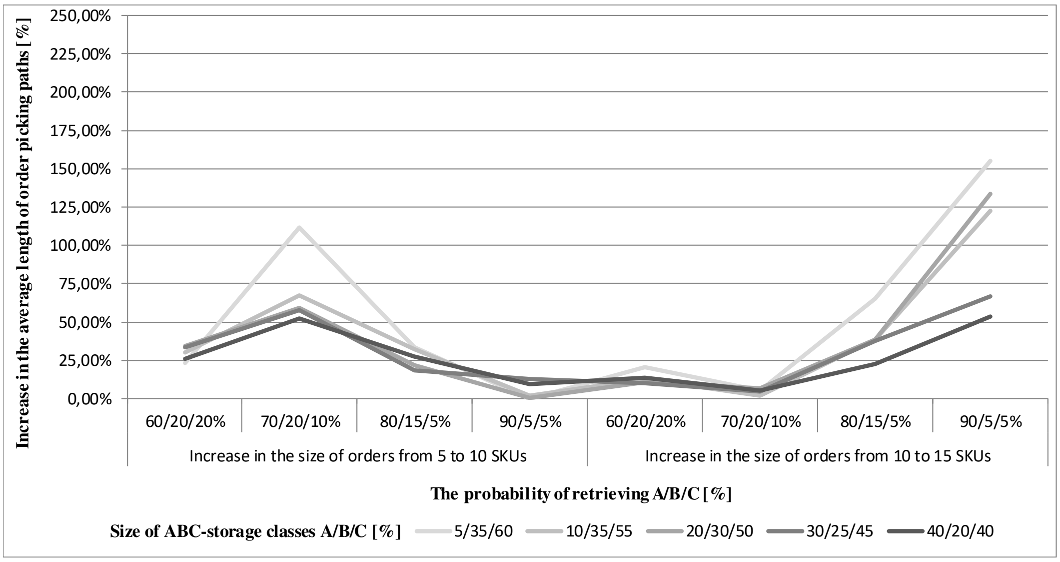
Source: authors' research

Fig. 4. The changes of the average length of order picking paths for the Within-Aisle storage strategy and the depot located in the corner of a warehouse (the bottom left one) depending on the order size



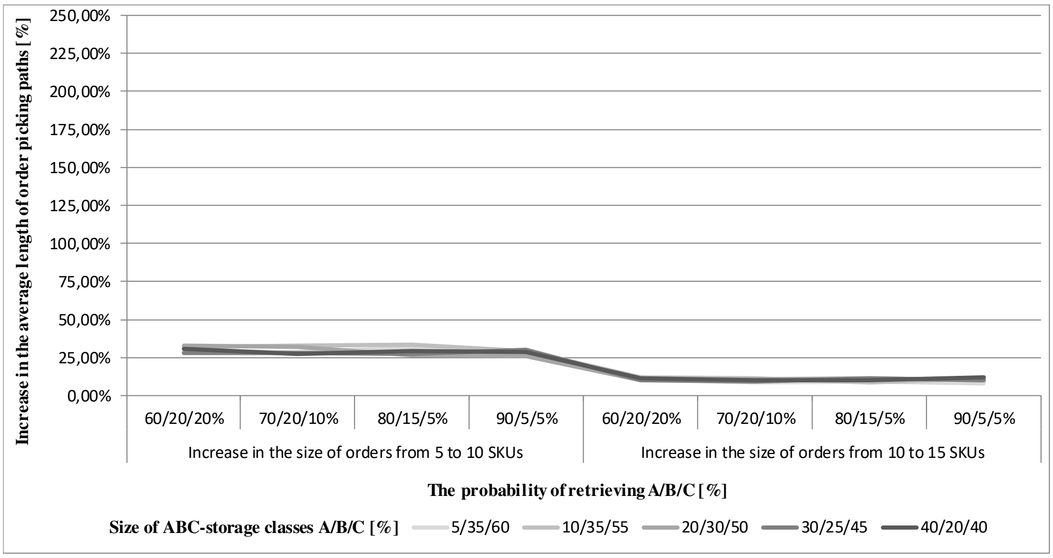
Source: authors' research

Fig. 5. The changes of the average length of order picking paths for the Random storage strategy and the depot located in the corner of a warehouse (the bottom left one) depending on the order size



Source: authors' research

Fig. 6. The changes of the average length of order picking paths for the Within-Aisle storage strategy and the depot located in the middle of a front aisle depending on the order size



Source: authors' research

Fig. 7. The changes of the average length of order picking paths for the Random storage strategy and the depot located in the middle of a front aisle depending on the order size

In general, the picking path's length is sensitive to the size of orders, which is commonly recognized (what turned out to be more crucial here were the changes from 10 to 15 than from 5 to 10 lines/items to be picked), but also to the probability of retrieving items belonging to particular ABC-storage classes. However, both the dependences are not direct ones. It can be stated than the distance to be covered depends more on the number of aisles (vertical ones) to be traversed than their (close or far) location in relation to the depot, thus the length of the horizontal aisles (front and back ones) to be covered. That is why the increase in the picking paths' length is higher when changing order size from 5 to 10 than from 10 to 15, when the Within-Aisle storage strategy is considered. This is not the case for the Random storage strategy. Extra lines on an order add more aisles to be traversed for B-and C- storage classes than for class A, which is relatively narrow and thus located in the small number of aisles. For comparison, see the study by Dijkstra and Roodbergen [2017]. The authors consider a similar situation (the order sizes, in fact, numbers of picks per route of 2, 10 and 20 lines, the probability of retrieving items belonging to a particular ABC-storage classes being 80/15/5 and 50/30/20% and the size of ABC-storage classes of 20/30/50%). The results are partially coherent: more aisles (in the case of the analysis presented here and also more lines/items on orders) longer distances to be covered. However, according to Dijkstra and Roodbergen's [2017] study, the size of orders changed from 2 to 10, resulting in a much more higher increase in the picking paths' length than from 10 to 20 lines/items to be picked. Both Dijkstra and Roodbergen's [2017] analysis and the present one revealed some specific probabilities of retrieving items belonging to a particular ABC-storage classes, resulting in higher or lower increases in the length of picking paths.

CONCLUSIONS

The overriding aim of the analysis was to find the relationship between the length of picking paths determined using the S-shape method and such parameters as the storage strategy, the depot location, the order size, the ABC-storage class size and the probability of retrieving items belonging to particular ABC-storage classes (where the three last ones characterize a demand pattern). Combinations of values of these parameters defined 240 variants of a picking system analyzed.

In general, much better results and shorter average order-picking paths were obtained for the Within-Aisle storage strategy (in comparison to the Random one) for the depot located in the middle of a front aisle (in comparison to the depot located in the bottom-left corner of a warehouse).

The S-shape method for determining order-picking paths is one of the simplest and most frequently used. It is easy to implement and its logic is easy to comprehend, even for inexperienced warehouse pickers. One of the important drawbacks of this method is its inelasticity, since picking paths determined this way always have the same, characteristic shape resembling the "S" letter. As a result, this requires aisles containing at least one pick to be traversed entirely (with or without the exception of U-turn in the last, odd traversed aisle). Moreover, in some cases, it causes empty movements, but on the other hand, some aisles can be skipped due to there being no picks.

As a direction for future research, the analysis presented in this paper will be carried out for the other methods of determining order-picking paths to allow for a comparison with the S-shape one. Other (e.g. Across-Aisle) storage strategies will also be taken into consideration.

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ANALIZA DŁUGOŚCI ŚCIEŻEK KOMPLETACJI WYZNACZANYCH METODĄ S–SHAPE

STRESZCZENIE. **Wstęp:** Kompletacja to podstawowa czynność realizowana w magazynach. Koszty kompletacji stanowią ponad 60% kosztów magazynowania, a jej najbardziej pracochłonnym elementem jest przemieszczanie się pracowników. Dlatego planowanie ścieżek kompletacji odgrywa tak ważną rolę. Najczęściej stosowną tu metodą jest metoda S-shape.
Metody: Celem oceny długości ścieżek kompletacji dla różnych parametrów strefy składowania (lokalizacja pola odkładczego, strategia składowania), składowanych zapasów (wielkość grup asortymentowych ABC i prawdopodobieństwo pobrania) i zamówień klientów (liczba linii – 5, 10, 15) zdefiniowano 240 wariantów analizy i dla każdego z nich wykonano 100 symulacji ścieżki kompletacji wyznaczając jej średnią długość. Analizy przeprowadzono z wykorzystaniem arkusza kalkulacyjnego MS Excel oraz makr (VBA).
Wyniki: Zestawienie długości ścieżek kompletacji dla magazynu jednoblokowego o 320 miejscach składowania (wg strategii Within-Aisle i losowej) oraz kompletacji z poziomu podłogi. Uwzględniono lokalizację pola odkładczego w narożniku magazynu oraz na środku przedniej alejki głównej. Długość ścieżek kompletacji okazała się mocno zmienna zależnie od analizowanego wariantu. Najkrótsze ścieżki kompletacji zaobserwowano dla strategii składowania Within-Aisle, pola dokładczego zlokalizowanego w narożniku magazynu, liczby linii na zamówieniu 5 lub 10 oraz grup asortymentowych ABC o wielkości 5/35/60% lub 10/35/55% wszystkich 320 lokacji przy prawdopodobieństwie pobrania asortymentów z każdej z grup 90/5/5%.
Wnioski: Istnieją lepsze i gorsze warianty kompletacji wpływające istotnie na długość ścieżek planowanych metodą S-shape. Generalnie mniejsze znaczenie ma tu lokalizacja pola odkładczego (jakkolwiek najlepsze rozwiązanie uzyskano dla lokalizacji w narożniku magazynu, to lokalizacja na środku przedniej alejki głównej daje przeciętnie krótsze ścieżki kompletacji), a większe strategia składowania. Brak tej strategii (losowość) istotnie wydłuża długość ścieżek kompletacji (średnio o 50%).

Słowa kluczowe: magazynowanie, kompletacja, metoda S-shape, długość ścieżek kompletacji

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